AN INTERPRETATION OF CERTAIN CLASSICAL LAWS, PRINCIPLES, AND UNITS OF ELECTRICITY AND MAGNETISM IN TERMS OF THE ELECTRON THEORY

by

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INTRODUCTION

The classical period in the development of physics is considered to have ended about 1900 A. D. The outstanding achievements of the century then closing were the kinetic theory of heat, the wave theory of light, the electromagnetic theory of matter, the discovery and application of the phenomena of electromagnetism, and the beginning of the quantum theory. Numerous assumptions, hypotheses, and theories were offered at that time to explain the phenomena involved, many of them being philosophical in character and largely unsupported by experimental evidence. During that period the existence of the electron was unknown; therefore, it could not contribute to an understanding of observed phenomena. There was no single basis of broad interpretation (15).

In 1895 X-rays were discovered, followed by the discovery of radioactivity in 1896 and the photo-electric effect in 1897. These could not be explained in terms of classical theories. They were revolutionary,and served to explode the prevalent belief that physical discoveries were completed and the facts all known. They opened up a new and very fruitful field of investigation. The clue to the mystery was found in 1897 with the discovery of the elec-

tron, which, since that time, has figured very prominently in the development of modern physics (12)(16). It is with a phase of this transition period, during which old ideas are being interpreted in new terms and new concepts, that this thesis proposes to deal.

Two distinct methods of introducing into elementary physics explanations based on the electron theory are in use at present. (1) Placing a few brief statements concerning the physics of the electron in an appendix to an otherwise classical treatment; (2) interspersing modern concepts throughout the text as occasion seems to demand. In the first arrangement the amount of electron physics is inadequate, and, in the second, too scattered, to enable the student to modernize his ideas of physical phenomena. Therefore it is considered advisable first to present the most important laws, principles, and units pertaining to elementary electricity and magnetism in a representative classical manner, and then to restate them in terms of the electron theory, in the hope that such a study will contribute to the modernization and integration of these portions of college physics.

To that end the literature of electricity and magnetism has been searched, including many original papers contributed by leading scientists in this field since 1600 as well as

the works of today's highest authorities. Those concepts, originating in the classical period, which are capable of electron interpretation, have received special attention, while a few others, later in origin, have been included, especially where the new was found to aid in explaining the old.

References are given to prominent sources, where available. It is impossible, however, to make acknowledgments in every case since in the great mass of classical and contemporary literature, early ideas have been so disseminated as to become common property.

ELECTROSTATICS

Foreword

Electrostatics is the science of electricity at rest. It is the oldest branch of electrical science, the first records being found among the writings of the early Greeks who had learned that amber and a few other substances, when rubbed, acquired an attraction for light objects. The assumption was made that amber possessed a special "soul" and was considered so mysterious that further investigation was largely neglected until about 1600, when Gilbert discovered that many substances could be electrified by friction (12). His accounts aroused considerable interest

and during the next two hundred years many of the phenomena concerning stationary electric charges were worked out, along with speculations regarding the nature of electricity and certain hypotheses attempting to explain it. These speculations and hypotheses will be discussed first, followed by the more modern electron explanations.

Methods of Electrification

Electrification by Friction. Let a hard rubber rod be electrified by rubbing with cat's fur or flannel and then suspended by an insulating silk thread. If a second rubber rod is also electrified in the same way and brought near the first, they will repel each other (10). In a similar manner, if two glass rods are electrified by being rubbed with silk, they will mutually repel (7)(14).

On the other hand, if a rubber rod and a glass rod, electrified as above, are brought near each other, the two will attract. Also the silk cloth, with which the glass rods were rubbed, will repel the charged rubber rod, and the flannel, with which the rubber rod was rubbed, will repel the electrified glass rod (11).

From these experimental phenomena the following observations may be made:

a. There are two states of electrification (5). The

one produced on glass and other vitreous substances by friction with silk was arbitrarily named positive. The other, called negative, is found on sealing wax, rubber, and similar resinous materials when rubbed with flannel.

b. Bodies with like charges repel each other, while those with unlike charges attract. This fundamental law was discovered by Du Fay about 1733 (3)(12).

By other means, to be discussed later, it has been shown that:

c. When a charge of one kind is produced, an equal and opposite charge is produced at the same time; that is, substances rubbed together become oppositely and equally electrified.

d. Mechanical energy is expended in producing electrification.

e. When a positive charge disappears, an equal negative charge also disappears. Opposite charges neutralize each other.

f. The force between two small charged bodies varies directly as the product of their charges and inversely as the square of the distance between them. It also varies with the nature of the separating medium.

g. Charges are always multiples of an elementary unit charge (e) taken a whole number of times.

Electrification by Induction. Let any insulated conductor having no charge, such as B in Figure 1, be approached by a charged body A. Immediately B will exhibit a

Figure 1

charged condition, regardless of the intervening medium. It is said to be charged by induction and the charge on B is called an induced charge (6). If A is removed, B will lose the charge and return to its original state (11)(14).

If either of the bodies, one being charged and the other uncharged, is suspended by a silk thread so it is free to move, it will display attraction when the other body is brought near (9). If B is grounded while in the condition shown in Figure 1 by connecting it to earth by a wire or by touching it with the hand, the positive charge disappears and the negative charge is supplied by a flow of electrons from the earth. When A and the ground are removed, the negative charge distributes itself uniformly over the surface of B.

Investigations with proof plane and electroscope will reveal that:

a. The end of B nearer A will carry a charge opposite

in sign to that on A, while the farther charge will be of the same sign as the A charge. Attraction will occur between bodies A and B because the negative charge on B is closer to A than the positive charge. It will be shown later that the force between charges varies as the square of the distance.

b. No electricity passes between A and B in either direction. They are separated by a dielectric, or insulator.

c. The two opposite charges on B are equal. This may be proved by using two conductors, B and C, placed in contact as in Figure 2. When a negatively charged body A is

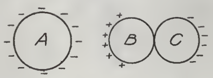

Figure 2

brought near, the charge developed on B is found to be positive and on C negative. If B and C are now separated and A is removed, the charges remaining on B and C will prove to be opposite. That they are also equal may be shown by their complete neutralization when B and C are again placed in contact.

d. The distribution of charge on a body is influenced

by neighboring charged bodies and by the medium separating them.

Electrification by Conduction. If a wire tied to the knob of a gold-leaf electroscope and insulated from other conducting materials is touched by a charged body, such as an electrified rod of sealing wax, the leaves of the electroscope quickly diverge. If the wire is replaced by a dry silk thread and the process is repeated, the leaves do not diverge but remain retracted.

By extending this experiment to all known substances the following observations have been made:

a. Many substances, known as conductors, readily permit the passage of electricity (6). A charge spreads all over the surface of the conductor touched and is transmitted to any other body that may be in contact (14). The metals and the solutions of most salts in water are the best conductors (7)(11).

b. Other substances, called non-conductors or insulators, do not permit the passage of electricity. The charge does not distribute itself over the body but remains in the neighborhood of the spot where electrification occurs. There is no sharp line of demarcation between conductors and insulators. Some materials even change from one class to the other when conditions change (9).

CLASSICAL THEORIES OF ELECTRIFICATION

Before the discovery of the electron about 1895 and the subsequent formulation of the electron theory, a number of theories on electrification had been offered. Although partially successful in explaining observed phenomena, they were based largely on conjecture unsupported by rigid experimental proof. All failed in one or more respects. The most prominent classical theories will be briefly reviewed.

The One-Fluid Theory. Franklin assumed that all matter contained a single "positive" fluid which could penetrate any conductor but accumulated only on the surface of insulators (12)(17). Matter took the place of the negative fluid and the particles of matter and of the fluid were self-repellent, but mutually attracting (13). Uncharged bodies contained a normal amount of the fluid, such that the attraction of matter for fluid outside the body just balanced repulsion due to the contained fluid. A body was plus, or positively, charged if it contained an excess of the fluid, and minus, or negatively, charged if it contained less than normal. Glass became electrified by friction because in being expanded by the heat it took up more than its share of the fluid, which it gave up again on cooling. The theory held that conductors could take up any

amount of the fluid and store it throughout their substance, while insulators could only store it on their surfaces. Each portion of the electric fluid was supposed, for reasons unknown, to repel every other portion directly (5).

This theory explained quite well how opposite charges neutralize each other and why a negative charge cannot be developed without at the same time producing an equal, positive charge. It failed to explain the fundamental difference between insulators and conductors, and succeeded poorly in explaining both frictional electrification and charging by induction. It was not universally adopted.

One direct and important result of this theory was Franklin's suggestion of the terms "positive" and "negative" to designate the kinds of charges, instead of "vitreous" and "resinous" in previous use (13). This improvement in terminology was generally adopted and still persists. However, the assumptions made in the application of the terms was most unfortunate. "Positive" was arbitrarily and without experimental proof taken to mean an excess of the electric fluid, and "negative" a deficiency. Thus the fluid was believed to flow from positive to negative, and, before the mistake was discovered, one hundred fifty years of prolific electrical development in both scientific and commercial lines had established many of the laws of current flow

and the rules of practical application. Had the interpretation of the terms been reversed from the beginning, the present confusion in the conception of current direction would have been avoided.

<u>The Two-Fluid Theory</u>. This is credited to Du Fay (3). He postulated two distinct kinds of electricity, calling them "vitreous" and "resinous" (13). Both were indestructible. An uncharged body contained equal quantities of the two fluids, while a charged body contained an excess of one or the other (6)(13). Vitreous electricity was the kind found in glass, rock crystal, precious stones, hair of animals, and many other bodies. Resinous electricity occurred on amber, copal, gum-lac, silk, paper, and a large number of other materials (12).

The fluids, which were considered imponderable substances, were communicated in some unexplained way to these bodies by the process of electrification, and the substances, on account of their power of "action at a distance", were the cause of the mechanical force observed between electrified bodies (14).

This theory seemed to explain many of the simple phenomena of electrification and was quite generally accepted up to the advent of the electron theory, although, like the one-fluid theory, it was unsatisfactory on induction, the

effect of the dielectric on the behavior of charges, and the distinction between conductors and insulators.

The Ether-Strain Theory. Faraday believed that electrical forces were communicated by the insulating medium which separated electrified bodies, and was able to show that while the force between two charged conductors does not depend on the material used, or whether they are solid or hollow, it does depend on the nature of the dielectric. This has been called the "ether-strain" theory of classical times (12) (13).

Faraday found it convenient to represent the field of force about a charged body by elastic lines which he called "lines of force" (6). These lines indicated the direction and magnitude of the forces between charges. They extended from the surface of a positively charged body to some surface negatively charged and were rigidly attached to those surfaces. If the charges became neutralized, the lines of force disappeared. Attraction and repulsion were explained by assuming that the lines of force tended to contract lengthwise, thus pulling unlike charges together, and repelled each other laterally, pushing like charges apart. Although the ether-strain theory, as such, is now discredited, Faraday's conception of "lines of force" is still used by many writers to illustrate the properties of the

fields of force surrounding electrified and magnetized bodies.

By considering chiefly what happened in the medium between bodies rather than within the bodies themselves, Faraday explained the phenomena of electrostatic induction but failed on conduction. Maxwell later incorporated Faraday's ideas into his electromagnetic theory. The two theories, together with certain fundamental discoveries made by Faraday and others, led directly to the electron theory and have been largely included in it.

THE ELECTRON THEORY OF ELECTRIFICATION

The electron theory offers the most complete and satisfactory explanation of electrical phenomena ever formulated. It does not invalidate the experimental facts of classical physics but serves to explain those facts more minutely and to integrate the several divisions or branches of physics into a more unified whole.

This theory holds that the atoms of all matter are made up of positive and negative charges of electricity and nothing else, except the energy associated with them (10). According to Rutherford and Bohr, a model atom consists of a nucleus, or central group of protons, having a small number of electrons associated with it, and other

electrons revolving in circular or elliptical orbits about the nucleus (6). All the atoms of any one element are alike. The atoms of different elements vary in the number and arrangement of the electrons and protons in their structure. Each electron carries a certain unvarying negative charge, and each proton an equal and constant positive charge. In a normal atom electrons and protons are equal in number, so the atom as a whole is neutral (9). The electron orbits constitute energy levels spaced at different distances from the nucleus, an outer orbit containing more energy than an inner one. By absorbing energy in quanta, corresponding to the difference in energy between levels, an electron may jump from an inner orbit to one farther out (2). If it absorbs sufficient energy to carry it entirely out of the atom, it becomes a free electron, or negative ion, while the remainder of the atom, now possessing an unneutralized proton, becomes a positive ion. Since this may happen simultaneously to many of the atoms of a body, under which condition the free electrons are usually transferred to remote parts or removed entirely, the body as a whole exhibits a charge. This charge is positive if the body is deficient in electrons and negative if more than the normal numbers of electrons have collected on it (10). An atom that contains more electrons than protons is also called a negative ion. In Figure 3 are conventional

Figure 3. Charges and Their Reactions. The two free electrons, or negative ions, in (1) repel. In (2) repulsion is due to the excess of protons in each atom. The free electron in (3) is repelled by the negative ion. Atoms with an excess of electrons repel, as shown in (4). In (5) the attraction of a positively charged atom for a free electron is shown. Neutral atoms, as in (6), weakly attract each other due to the force of gravity. Gravitational force causes neutral atoms to attract free electrons, when near, as in (7), while the attraction in (8) is caused by the unlike charges of the atoms. These drawings are conventional and are not intended to represent other features of atoms than those enumerated.

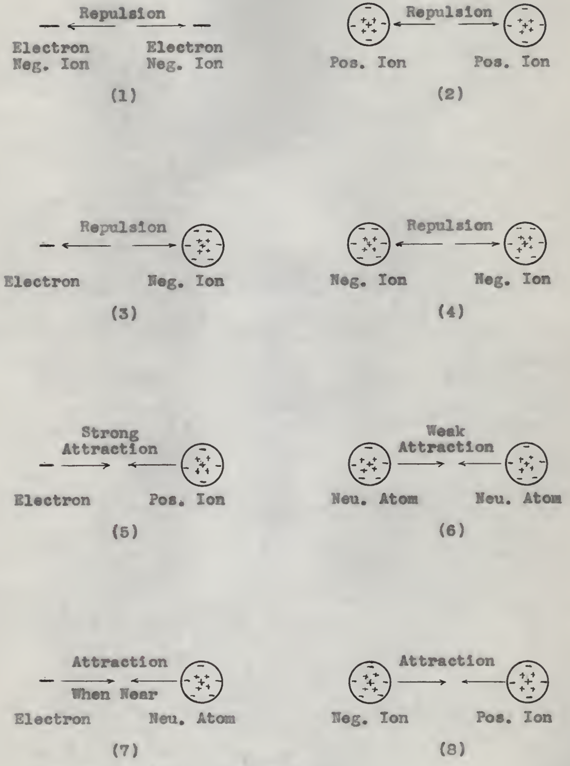
Repulsion
Electron
Neg. Ion
Electron
Neg. Ion
(1)
Repulsion
Pos. Ion
Pos. Ion
(2)
Repulsion
Electron
Neg. Ion
(3)
Repulsion
Neg. Ion
Neg. Ion
(4)
Strong
Attraction
Electron
Pos. Ion
(5)
Weak
Attraction
Neu. Atom
Neu. Atom
(6)
Attraction
When Near
Electron
Neu. Atom
(7)
Attraction
Neg. Ion
Pos. Ion
(8)

Figure 3

drawings of neutral (normal) atoms and positive and negative ions showing the unbalance between charges and the forces resulting therefrom.

The outer electrons of many kinds of atoms are not strongly held by the positive charge on the nucleus and a suitable acquisition of energy serves to displace them, or even drive them from the atom and make them free or roaming. Energy for such purposes may be supplied from various sources, among them being friction, electric and magnetic fields, heat, light, electronic impact and chemical action.

Charging by Friction. When ebonite is rubbed with fur the mechanical energy supplied is partly expended in removing electrons from the fur, leaving it positive, and depositing them on the ebonite, making it negative (8). Likewise, glass, when rubbed with silk, loses electrons to become positive in charge, while the silk gains them to become negative. Since the electrons lost by one body are the same as those gained by the other, positive and negative charges are equal (5).

Attraction and Repulsion. The enormous force of repulsion existing between free electrons, and between unneutralized protons, explains why like charges repel, while the equally great attraction of electrons and protons for each other accounts for the behavior of opposite charges.

These forces, the explanation of which is undetermined at present, are equivalent to 2.275 x 10^{-19} dynes between two electrons one centimeter apart. They are transmitted by the "electric field", which is a field of radiant energy replacing the ether of classical physics. Due to this field and within its bounds all electrical action takes place (5).

Displaced or mobile electrons, together with the unbalanced energy conditions accompanying them, are responsible for electrical phenomena of every sort, all of which are collectively expressed in popular terminology by the one word "electricity".

Charging by Induction. In this process use is made of the electric forces just mentioned. The effect of an approaching positive charge such as exists on A, Figure 2, upon an insulated neutral conductor, BC, is to attract electrons to the nearer end, B, creating there a negative charge, or surplus of electrons, and leaving at the farther end, C, a number of positive ions, constituting a positive charge. Since electrons have not been taken from or added to BC, the charges induced on it are not permanent but will merge and neutralize when A is removed (9).

If the body BC is grounded, or touched with the hand, while a charge is being induced upon it by bringing up the

positive body A, the electrons necessary to establish the negative charge at B will not be drawn from the distant atoms at C but from the earth. No internal strain will be imposed upon the atoms of BC and a positive charge will not appear. If the ground connection and the positive body A are now removed, the electrons from the external source will spread uniformly over the surface of BC, giving it a negative potential throughout.

Charging by induction may occur only if the body is a conductor in which electrons are free to move and are not closely confined to the atoms. Since in an insulator, or dielectric, electrons cannot leave the atoms, a charge does not spread but remains in the region where electrification takes place. Due to electric force a displacement of the outer electrons of the atoms occurs, whereby their orbits become distorted into abnormal positions and shapes. They return to normal, however, when the force is withdrawn and become distorted in the opposite direction if electrification is reversed. This slight electron movement within the atoms of a dielectric was named by Maxwell a "displacement current" (16). It is especially useful in explaining the behavior of electrostatic condensers (8).

Coulomb's Law and the Electrostatic Coulomb

Let two gilded pith balls be suspended by silk threads, as in Figure 4, and electrified by contact. If the two balls thus become charged alike, they repel each other and

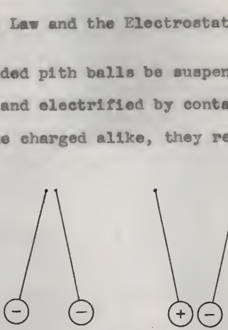

Figure 4

swing apart, but with unlike charges they attract (9). Upon this characteristic and fundamental behavior of static charges, the electrostatic system of units is established.

Coulomb's Experiment. The first exact quantitative measurement of electric force was made by Coulomb using a torsion wire balance and employing the above principle (8). In this instrument he hung a long fine wire vertically from a torsion head graduated in degrees. At the lower end of the wire a bar of very light insulating material was suspended horizontally within a glass jar (12). To one end of this bar he attached a gilded pith ball, while through the cover of the jar he inserted an insulated metal ball

carrying a charge. When the metal ball touched the pith ball the charge divided equally between them and the pith ball was repelled to such a distance that the twist in the wire balanced the force of repulsion. He read the deflection of the pith ball on a scale inscribed on the side of the jar. When the twist in the wire was increased by means of the torsion head until the two balls were just half as far apart, he found the twist in the wire was four times as great as before, and when the balls were one-fourth as far apart the twist was sixteen times as great (11).

To determine the effect of a change in the quantity of charge, the charged metal ball was withdrawn and touched to a similar uncharged ball. This again divided the charge so that when returned to its place within the instrument the ball carried only half its previous charge. The repulsion between the metal ball and the pith ball was then found to be only half as great.

Coulomb's Law. From many such experiments Coulomb concluded that the force between two small charged spheres is inversely proportional to the square of the center-to-center distance between them, and directly proportional to the product of the charges (6). This law holds rigorously when the spheres are points, the distance between them is small, and the medium is a vacuum. For other conditions

the algebraic expression of the law is:

$$F = \frac{q\ q'}{k\ r^2}$$

where F is the force, q and q' are the charges, r is the distance between the charges, and k is a constant which depends upon the units used, and, as shown by Faraday, the characteristics of the medium. This law was proved experimentally by Maxwell, using two conducting spheres, one inside the other (12).

The Electrostatic Coulomb. Let the force F equal one dyne and the distance r one centimeter in a vacuum. Then the charges q and q' in the above equation will each be a unit charge in the electrostatic system, or one electrostatic coulomb. Since the charge on the electron is 4.774×10^{-10} electrostatic units, it follows that the number of electrons in one statcoulomb is equal to $\frac{1}{4.774 \times 10^{-10}}$, or 2,095,000,000 electrons (8) (10).

The electron is the natural unit of electric charge but is not generally used in the force equation stated above for two reasons: (1) If the charges were each one electron and their distance apart one centimeter, the force would be only 22.8×10^{-20} dynes in a vacuum, and less in other media. This force is extremely small. (2) When these electrical phenomena were first measured the electron was unknown, but concepts of mechanical units were well

understood and already widely used. So the electrostatic system of electrical units, as well as the other systems in common use, are based on mechanical principles and units (5).

The Charge on the Electron. The charge e on the electron is found to be one of nature's fundamental constants, ranking with the velocity of light and the universal constant of gravity. Since it was required in evaluating the electrical units mentioned, as well as many atomic, molecular, and radiation constants, its exact determination early commanded the attention of the world's leading scientists (13).

In 1874 the Irish physicist, G. Johnstone Stoney, predicted the "atom of electricity" and calculated its approximate charge (5). Closer values of e were obtained by Townsend in 1897 (6), working with X-rays and radium. Sir J. J. Thomson improved the method and found more exact values the following year (2). The next advance was made by C. T. R. Wilson in 1903 by employing a cloud of fine water droplets (2). Beginning about 1906, Wilson's method was modified and perfected by Millikan in a series of brilliant experiments covering a period of several years. By 1917 he had completed and published his famous oil drop experiment by which he determined, in what is believed to be

final form, the exact value of the charge on the electron to be 4.770×10^{-10} electrostatic units (13). Owing to the fundamental nature and great importance of this experiment a brief account is here outlined, much of it being directly quoted.

Previous experiments on water droplets had encountered certain sources of error, chief of which were: "(1) The lack of stagnancy in the air through which the drop moved; (2) the lack of perfect uniformity of the electrical field used; (3) the gradual evaporation of the drops, rendering it impossible to hold a given drop under observation for more than a minute or to time a drop as it fell under gravity alone through a period of more than five or six seconds; and (4) the assumption of the validity of Stoke's Law.

"The method which was devised to replace it was not entirely free from all of these limitations, but it constituted an entirely new way of studying ionization and one which at once yielded important results in a considerable number of directions.

"In order to compare the charges on different ions, the procedure adopted was to blow with an ordinary commercial atomizer an oil spray into the chamber D, Figure 5. The air with which this spray was blown was first rendered

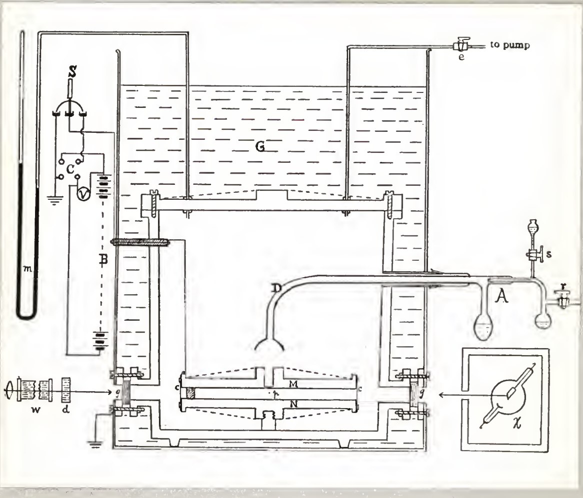

Figure 5. "A, atomizer through which the oil spray is blown into the cylindrical vessel D. G, oil tank to keep the temperature constant. M and N, circular brass plates, electrical field produced by throwing on 10,000-volt battery B. Light from arc lamp a after heat rays are removed by passage through w and d, enters chamber through glass window g and illuminates droplet p between plates M and N through the pinhole in M. Additional ions are produced about p by X-rays from the bulb X." From Millikan (13).

dust-free by passage through a tube containing glass wool. The minute droplets of oil constituting the spray, most of them having a radius of the order of a one-thousandth of a millimeter, slowly fell in the chamber D, and occasionally one of them would find its way through the minute pinhole p in the middle of the circular brass plate M, 22 cm. in diameter, which formed one of the plates of the air condenser. The other plate, N, was held 16 mm. beneath it by three ebonite posts a. By means of the switch S these plates could be charged, the one positively and the other negatively, by making them the terminals of a 10,000-volt storage battery, B, while throwing the switch the other way (to the left) short-circuited them and reduced the field between them to zero. The oil droplets which entered at p were illuminated by a powerful beam of light which passed through diametrically opposite windows in the encircling ebonite strip c. As viewed through a third window in c on the side toward the reader, it appeared as a bright star on a black background. These droplets which entered p were found in general to have been strongly charged by the frictional process involved in blowing the spray, so that when the field was thrown on in the proper direction they would be pulled up toward M. Just before the drop under observation could strike M the plates would be short-circuited and

the drop allowed to fall under gravity until it was close to N, when the direction of motion would be again reversed by throwing on the field. In this way the drop would be kept traveling back and forth between the plates. The first time the experiment was tried an ion was caught within a few minutes, and the fact of its capture was signaled to the observer by the change in the speed with which it moved up when the field was on. The significance of the experiment can best be appreciated by examination of the complete record of one of the early experiments when the timing was done merely with a stop watch.

"The column headed t_g, in Table I, gives the successive times which the droplet required to fall between two fixed cross-hairs in the observing telescope whose distance apart corresponded in this case to an actual distance of fall of .5222 cm. It will be seen that these numbers are all the same within the limits of error of a stop-watch measurement. The column marked t_F gives the successive times which the droplet required to rise under the influence of the electrical field produced by applying in this case 5,051 volts of potential difference to the plates M and N. It will be seen that after the second trip up, the time changed from 12.4 to 21.8, indicating, since in this case the drop was positive, that a negative ion had been

TABLE I

Time Required for Fall and Rise of Drop

t_g	t_F
13.6	12.5
13.8	12.4
13.4	21.8
13.4	34.8
13.6	84.5
13.6	85.5
13.7	34.6
13.5	34.8
13.5	16.0
13.8	34.8
13.7	34.6
13.8	21.9
13.6	
13.5	
13.4	
13.8	
13.4	

Mean 13.595	

caught from the air. The next time recorded under t_F, namely, 34.8, indicates that another negative ion had been caught. The next time, 84.5, indicates the capture of still another negative ion. This charge was held for two trips, when the speed changed back again to 34.6, showing that a positive ion had now been caught which carried precisely the same charge as the negative ion, which before caused the inverse change in time, i.e., from 34.8 to 84.5.

"In order to obtain some of the most important consequences of this and similar experiments we need make no

assumption farther than this, that the velocity with which the drop moves is proportional to the force acting upon it and is independent of the electrical charge which it carries. Fortunately this assumption can be put to very delicate experimental test, as will be presently shown, but introducing it for the time being as a mere assumption, as Townsend, Thomson, and Wilson had done before, we get

$$\frac{V_1}{V_2} = \frac{mg}{Fe_n - mg} \text{ or } e_n = \frac{mg}{FV_1}(V_1 + V_2)$$

The negative sign is used in the denominator because V_2 will for convenience be taken as positive when the drop is going up in the direction of F, while V_1 will be taken as positive when it is going down in the direction of g. e_n denotes the charge on the drop, and must not be confused with the charge on an ion. If now by the capture of an ion the drop changes its charge from e_n to e_{n1}, then the value of the captured charge e_1 is

$$e_1 = e_{n1} - e_n = \frac{mg}{FV_1}(V_2' - V_2)$$

and since $\frac{mg}{FV_1}$ is a constant for this drop, any charge which it may capture will always be proportional to $(V_2' - V_2)$, that is, to the charge produced in the velocity in the field F by the captured ion. The successive values of V_2 and of $(V_2' - V_2)$, these latter obtained by subtracting successive

values of the velocities given under V_2, are shown in Table II.

TABLE II

Values of V_2 and of $(V_2' - V_2)$

V_2	$(V_2' - V_2)$
$\frac{.5222}{12.45} = .04196$	
	$.01806 \div 2 = .00903$
$\frac{.5222}{21.5} = .02390$	
	$.00885 \div 1 = .00885$
$\frac{.5222}{34.7} = .01505$	
	$.00891 \div 1 = .00891$
$\frac{.5222}{85.0} = .006144$	
	$.00891 \div 1 = .00891$
$\frac{.5222}{34.7} = .01505$	
	$.01759 \div 2 = .00880$
$\frac{.5222}{16.0} = .03265$	
	$.01759 \div 2 = .00880$
$\frac{.5222}{34.7} = .01505$	
	$.00891 \div 1 = .00891$
$\frac{.5222}{21.85} = .02390$	

"It will be seen from the last column that within the limits of error of a stop-watch measurement, all the charges

captured have exactly the same value save in three cases. In all of these three, the captured charges were just twice as large as those appearing in the other charges. Relationships of exactly this sort have been found to hold absolutely without exception, no matter in what gas the drops have been suspended or what sort of droplets were used upon which to catch the ions. In many cases a given drop has been held under observation for five or six hours at a time and has been seen to catch not eight or ten ions, as in the experiment above, but hundreds of them. Indeed, I have observed, all told, the capture of many thousands of ions in this way, and in no case have I ever found one the charge of which, when tested as above, did not have either exactly the value of the smallest charge ever captured or else a very small multiple of that value. <u>Here, then, is direct, unimpeachable proof that the electron is not a "statistical mean", but rather the electrical charges found on ions all have either exactly the same value or else small exact multiples of that value.</u>" (13).

Potential. Potential Difference

<u>Absolute Potential</u>. The absolute potential at a point is equivalent to the work required to bring a unit quantity of electricity from infinity to the point considered (14).

The potential at infinity is assumed to be zero, which, in practice, is taken as the potential of the earth (6). Thus, the absolute potential at a point equals the work done in moving a unit charge of electrons from the earth to the point, if negative potential is desired, or from the point to earth, if positive (11).

Potential Difference. This is essentially the same thing; that is, the work necessary to move a charge from one point or surface to another, except that zero potential is not necessarily involved (8). Let the plates of a condenser be the surfaces considered, and the charge be one electrostatic coulomb. Then, if unit work is done on the charge so that potential difference increases, 2.095×10^9 electrons are transferred from the positive to the negative plate. The condenser is charging and energy is being stored in the electric field. If the condenser is discharging, an equal amount of work is being done by the electrons as they move from the negative to the positive plate, the potential difference is now decreasing, and electric energy is being dissipated in other forms, such as heat.

Electrostatic and Practical Units (6). If W is the work required to transfer a charge q, and V is the potential difference (PD) established, then $V = PD = W/q$. In the electrostatic system of units this becomes:

$$\text{Stat-volt} = \frac{\text{Unit Work}}{\text{Unit Quantity}} = \frac{\text{Erg}}{\text{Stat-coulomb}}$$

$$= \frac{\text{Erg}}{2.095 \times 10^{9} \text{ electrons}}$$

In the practical system the unit of work is the joule (10^7 ergs), the international volt is the unit of potential difference, and the coulomb is the unit of electrical quantity. Then, in this system,

$$\text{Volt} = \frac{\text{Unit Work}}{\text{Unit Quantity}} = \frac{\text{Joule}}{\text{Coulomb}} = \frac{\text{Joule } (10^{7} \text{ ergs})}{6.285 \times 10^{18} \text{ electrons}}.$$

MAGNETISM

The Behavior of Magnets

Let a permanent magnet having one north pole and one south pole located near the ends, be broken. New poles will be found to have formed at the fracture and each piece will have become a complete magnet. If the breaking process is continued until the fragments are microscopic in size, each piece will still be magnetized and will exhibit north and south poles of equal strength (9)(10)(12)(14).

If a test tube filled with hard steel filings is placed in a strong magnetic field and jarred slightly, the filings will become so arranged that their greatest lengths lie parallel to the magnetic field. If the body of filings

is now gently removed from the magnetizing field, so the filings remain in position, it will show all the properties of a permanent magnet, including a field of its own. However, if the filings become agitated so the parallel arrangement is broken up, the magnetic properties of the filings as a whole disappear, although individual particles, when isolated, still will be found magnetized.

From these experimental phenomena the following observations may be made (11):

a. The fragments of a magnet, large or small, always have two equal and opposite poles.

b. Unlike poles attract each other and like poles repel.

c. A magnet, when free to turn, will always orient itself so that its magnetic meridian is parallel to an outside magnetic field.

These observations, and others concerning magnets, indicate that magnetism is a condition which exists throughout the whole of a magnet and is not merely a surface state. All substances have been found to respond in some manner to the influence of magnetism. Some are paramagnetic, having permeability greater than that of air; others diamagnetic, with less permeability than air. Paramagnetic substances, when free to move, are always drawn into the strongest part

of a magnetic field and align themselves parallel to it. They are attracted by a magnet. Iron, nickel, cobalt, and a number of alloys exhibit this property strongly (6). Diamagnetic substances align themselves crosswise of a magnetic field and are repelled by it so that they move out of the field (14). Antimony and bismuth are examples.

Classical Theories of Magnetism

The Fluid Theory. Early theories of magnetism often linked it with the mysterious and the occult. The Greeks believed lodestone possessed a "special soul". Later it was held that the behavior of magnets was due to an imponderable substance in the form of two fluids, opposite in kind but equal in quantity, which were separated by the process of magnetization. The positive fluid collected at one end to form the north pole, while the south pole was due to the collection of negative fluid at the other end. Both these fluids had the property of repelling the fluid of like kind and attracting that of opposite kind, the reason being unknown.

The discovery that breaking a magnet did not isolate the north pole from the south, and thus divide the fluids, made a change necessary to the assumption that the magnetic fluids were possessed by each particle of iron within which the separation occurred.

The theory accounted for magnetic induction and the distribution of magnetic forces in a magnet, but failed on saturation, loss of magnetic properties above a certain temperature, and the lack of an insulator for magnetism. Certain other phenomena unknown to the early investigators also would have been unaccounted for. In the light of experimental facts then established the fluid theory was quite satisfactory and was generally accepted up to the early part of the nineteenth century.

The Amperian Theory. Ampere, Weber, and Ewing laid the foundation of the classical theory of magnetism generally accepted before the discovery of the electron and the advent of the electron theory (10). Ampere offered the hypothesis, which was not inconsistent with any facts then known, that each molecule of a magnetic substance has an electric current flowing around it, without resistance below certain temperatures (7). This deduction came from his investigations of magnetism set up by currents flowing in coils of wire, though he was unable to say what constituted or caused the molecular currents (5) (12).

Weber did not attempt to explain the cause of magnetism itself but only to account for the behavior of magnetic bodies. He accepted Ampere's hypothesis and started with the assumption that each molecule of iron is a natural

magnet (6). In the unmagnetized condition he believed the molecular magnets have no definite arrangement, but under the influence of mutual attraction the north pole of one particle is drawn to the south pole of another, thus forming random closed groups or rings which confine the magnetic forces within the body of the iron and eliminate any tendency toward the formation of an external field. The process of magnetizing consisted of rearranging these little magnets under the influence of a strong impressed field until they are aligned parallel to the field, with their north poles pointing one way and their south poles the other.

Ewing extended the theory to explain the phenomena of saturation, hysteresis, and retentivity. He suggested that the natural magnetic attraction of the molecules holds them in stable groups with considerable force. When an increasing magnetic field is applied externally to such groups, the molecules tend to turn, but with some difficulty at first, until the magnetizing influence is made strong enough to cause the groups, one by one, to become unstable. Then, between certain relatively small limits of increase in the external field, the groups rapidly break up and reform in new stable groups with the tiny magnets more nearly parallel to one another. This new alignment greatly in-

creases the intensity of the field and accounts for the rising portion of the saturation curve. After this a further and much greater increase in magnetizing force merely brings the magnets more and more in line, complete saturation being reached when they are all arranged in parallel rows. Thus the three stages of magnetization were explained (7).

When the external field is diminished the stability of the new groups continues. They do not break down and return to their original condition until the magnetizing force is considerably weakened and usually reversed for complete demagnetization. In the case of hard steel there was assumed to be a frictional resistance between the molecules, which makes both magnetization and demagnetization more difficult than in soft iron. For this reason not only the original or natural groups but also the final groups are very reluctant toward change, so that, after being aligned, if the magnetizing force is removed, the molecules retain their parallel groupings to a large extent, making the magnetized condition permanent. These explanations of saturation, retentivity, and hysteresis were undisputed for many years but do not seem to be fully supported by the latest experiments, which indicate that the spinning electron is the elementary magnetic particle (1).

If a permanent magnet is heated it loses its magnetism, and at about 770° C. iron is no longer attracted by another magnet (14). In explanation of this the deduction is made from heat theory that at the higher temperatures thermal agitation prevents alignment by a magnetic field and groupings of any kind are extremely unstable. Upon cooling, the magnetic qualities return. The same reasoning applies to nickel and cobalt, except at lower temperatures.

Electron Theory of Permanent Magnets

Interpreted according to the electron theory, magnetism is atomic or electronic in origin. If Bohr's hypothesis of atomic structure is accepted (15), magnetic characteristics may be ascribed to every atom due to its revolving electrons (8). The revolution of the electrons about the nucleus of an atom constitutes circular currents, similar on a very small scale to the movement of a large number of electrons flowing in a circular coil of wire. Each revolving electron is thus believed to have a magnetic field (9).

If the electron orbits are so oriented that their magnetic fields cancel, the atoms will be, in effect, nonmagnetic. This is not generally the case, however, as in most materials the orbital arrangement is thought to be such that a resultant field exists, making each atom mag-

netic. Due to mutual attraction, these atomic magnets naturally arrange themselves more or less at random in closed groups whose magnetic axes point in every direction and whose magnetism is either confined to the group or neutralized by other groups, so no external field exists and the substance as a whole is nonmagnetic. This is illustrated in Figure 6 in which, for simplicity, each circle

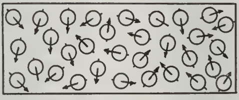

Figure 6

represents a group of atoms and the arrow points in the direction of the resultant field of that group. When an external field is applied the motions of the electrons are supposed to be changed slightly, in some cases so that the substance exhibits diamagnetism and in other paramagnetism, depending on electron arrangement or behavior within the atoms.

The nature of this behavior is uncertain. Recent experiments seem to indicate that the individual atoms of

diamagnetic substances orient themselves with their resultant magnetic axes opposed to the external field, or at right angles to it, which would cause a tendency to move out of the field, while in paramagnetism the resultant axes become aligned with the field and the substance moves farther into it. Also in ferromagnetism, an applied magnetic field is believed to orient the electron orbits to such an extent that the minute magnets all swing into the field, and by thus adding their resultant fields build up a very intense magnetization. This orientation is largely retained in steel if it is tempered very hard. Figure 7

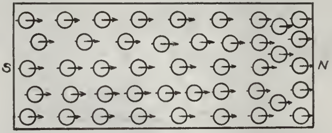

Figure 7

indicates the final positions of atoms or groups of atoms of a ferromagnetic substance in a very strong uniform external field, while Figure 8 represents conditions in a permanent magnet after the external field has been removed.

On the assumption that elemental magnets are due to revolving electrons, we may postulate how a sufficient

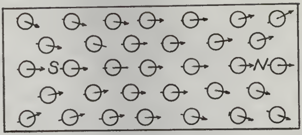

Figure 8

number of such electrons could make up a magnet. Let Figure 9 represent an idealized section of a ferromagnetic substance in which each atom has an electron current circu-

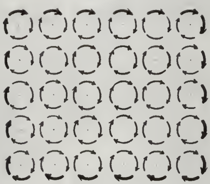

Figure 9

lating around it, as indicated by the arrows. At all interior points where atoms are adjacent, there are two currents in opposite directions which neutralize each other, leaving only the currents on the outer or free sides of the section to produce a resultant magnetization. The

field is due, therefore, to a current equal to the atomic current circulating around the outside of the section (5). The magnitude of this field is proportional to the resultant of all the electron orbits additively oriented and to the revolutions per second of the electrons. If the radius of the magnet is one centimeter and the field at the center exerts a force of one dyne, the circulating current is one abampere, or 10^{19} electrons per second.

The explanation of magnetism given above is not acceptable at present. Recent spectroscopic investigations of ferromagnetism have revealed no evidence of orientation either of molecules or atoms under the influence of an external field. If change occurs at all, it must be within the atom (10).

According to Bozorth (1), it appears to be due mainly to electron spin. Although the revolution of the electron about the nucleus of the atom is believed to yield a certain magnetic moment, it is the spinning of the electron on its own axis that supplies the greater portion of the magnetic effect, and all changes in magnetization are attributable to the orientation and parallel grouping of these electron spins.

The orbital paths of electrons are spaced or arranged in shells. Any shell is magnetically neutral which has an

equal number of electrons spinning in each direction, positive and negative. This condition applies to all the shells of many elements, but in the ferromagnetic substances certain shells contain more electrons spinning in one direction than the other and are therefore polarized. To be ferromagnetic, there must also exist the further condition that the spins in neighboring atoms be parallel and capable of orientation in groups or "domains" to be brought into alignment during the process of magnetization.

The true and complete nature of magnetism remains a discovery for the future, one of the intriguing mysteries of modern physics. Full treatment of its present status involves extensive use of the quantum theory and spin mechanics, which places it beyond the scope of this thesis.

Magnetic Moment. Magneton

If a bar magnet is placed in a magnetic field it will tend to align itself parallel to the lines of force with a couple proportional to the strength of the field and to the magnitude of a property of the bar known as its magnetic moment (8)(9)(11).

Since magnetism has been found to be subatomic in origin, it has been postulated that each atom possesses a resultant magnetic moment which is the summation of all the

uncompensated moments set up by the revolution of the electrons about the nucleus, the spin of the electron, the spin of the nucleus, or whatever it is that causes magnetism. This magnetic moment, which is responsible for the magnetic behavior of atoms, varies with the kind of substance (atoms) being stronger in some than in others. Investigation of this property by Weiss, Bohr, and others indicates that the magnitude of the magnetic moment of any atom, and therefore of any magnet, is always a multiple of an ultimate unit of moment, named by Weiss the magneton. This unit of magnetic action corresponds in magnetism to the elementary unit of electricity, the electron. Its magnitude is computed to be 9.175×10^{-21} electromagnetic units (2).

Unit Magnetic Pole. Coulomb's Law

An isolated magnetic pole never exists. A north pole and an equal south pole are always found on the same magnet. But for the purpose of measurement, a very long thin magnet has one pole so far removed from the other that the effect on each other is negligible. Coulomb, using such a magnet, studied the attractions and repulsions of magnetic poles and with his torsion balance discovered the law of magnetic force which bears his name (7)(12).

This law states that the force exerted by two poles

upon each other is directly proportional to the product of their individual forces and inversely proportional to the distance between them (9). The algebraic expression of this law is

$$f = \frac{m'm''}{k\, d^2}$$

where m' and m" are the quantities of magnetism in the two poles, k is a proportionality factor that depends on the units used and the medium between the poles, d is the distance between poles, and f is the mechanical force of repulsion or attraction, as the case may be. Upon this law is based the classical definition of the unit pole and the absolute system of electromagnetic units (10). Such a unit pole is one which, when placed one centimeter from an equal and like pole in air, repels it with a force of one dyne (6)(11).

ELECTRODYNAMICS

Foreword

Electrodynamics is the science of electricity in motion. If a copper wire or any series of solid conductors connects two points between which a potential difference is maintained, an electric current flows through the conduct-

ors. If a solution, such as salt dissolved in water, is made a part of the circuit, the current continues to flow, but if an air gap or other insulator is introduced, the circuit is broken and the current ceases (14).

Careful investigation of these and similar phenomena reveals that:

a. Current consists of elementary quantities of electricity moving under the force of an electric field and obeying certain natural laws (15).

b. Differences exist in the atomic structure of various materials that may be used in the circuit, causing some to be conductors, others insulators (10).

c. An electromagnetic field exists around a flow of electricity which will exert mechanical force and transmit energy.

d. Heat, magnetism, and chemical reactions develop in the circuit, varying with the materials used and the magnitude of the current. In such cases energy is expended and work done to maintain the potential difference, the energy being supplied by a battery cell, a generator, or other source of electromotive force, either primary or secondary.

e. If the conductor is a solution, it decomposes, and from certain solutions gases are liberated and metals deposited.

Classical Theories of Electrodynamics

Explanations Varied. Many of the phenomena of current flow were not explained by classical physics. Resistance, the production of heat and magnetism, and the fundamental difference between conductors and insulators, are examples. From the time of Volta electric current was believed to be a continuous transfer of electricity around the circuit, all in one direction in the one-fluid theory and equally in both directions in the two-fluid theory. This latter view agreed with the laws of electrolysis, as discovered by Faraday, but failed to explain the mechanical attraction and repulsion of currents for each other, which clearly were not due to static charges. Since the mass of a conductor was not altered by current flow, those fluids were thought to be imponderable.

Weber offered the hypothesis that moving charges react on one another with forces due to their velocities as well as with static forces, and assumed that these actions take place in some direct manner, depending on the distance between the currents and not on the medium separating them. Faraday disagreed with this view (12), holding that electric and magnetic actions take place by means of physical lines of force through the interaction of some medium,

known as the ether. Maxwell gave this latter view mathematical form and thereby attempted to show that the flow of electricity in a conductor is accompanied by a displacement in the surrounding dielectric which produces the electric and magnetic fields and serves as a reservoir and conveyor of energy (6). Poynting added the theorem that to start this ethereal mechanism in action requires energy which is supplied by the source only at a certain rate. At first this energy is divided between that expended in the circuit and that stored in the field, but when the current reaches the steady state, the field is maintained without further expenditure of energy. Thereafter, the flow of energy from the source all passes through the dielectric, finally reaching the conductor and being transformed by it.

Electron Theory of Electrodynamics

The electron theory offers the best explanation of electric current so far advanced. Much has been verified by experiment. It recognizes three kinds of current, conduction current in solids, displacement current in dielectrics, and convection current in liquids and gases. All involve atomic structure and the behavior of electrons and protons.

<u>Conduction Current. Conductors. Insulators</u>. Metallic conduction current consists of the transfer, or movement of free electrons from atom to atom through the conductor (5). Such a current may exist in any solid that contains electrons capable of escape from their parent atoms to drift or flow in a continuous stream (9). These electrons are called roaming, detachable, or conduction electrons. A good conductor is a material which releases and passes a large number of electrons in this manner under a slight electric force or potential difference (2), while a poor conductor not only contains fewer detachable electrons but these require a higher potential difference to detach them from their atoms and cause them to drift. The electrons of insulators are believed to be tightly bound within the atoms and are released, if at all, only under the pressure of an extremely high potential (5). Ordinarily, the electron orbits of an insulator may become considerably distorted in the direction of an electric force but will return to normal when the force is removed. This slight movement of electrons in a dielectric is called a displacement current (6).

The chief difference between conductors and insulators, whereby a list of known substances quite gradually grades off from one extreme to the other without any sharp

line of demarcation, is believed to be largely, if not entirely, due to the one feature of atomic structure mentioned above, that of detachable electrons.

Protons in solids tend to move in a direction opposite to that of electrons, but, due to their greater mass and fixed positions within atomic nuclei, movement does not occur to any extent. As they are essential, without variation in number or arrangement, to atomic structure, to remove them would destroy the atom. Atoms of different elements are unlike, and if proton movement were appreciable it would carry whole atoms across the junctions of metallic circuits and cause the mixing of unlike substances. This has never been detected in solids at normal temperatures and pressures.

<u>Manner of Current Flow</u>. The manner in which electrons flow through a metallic conductor has been found to be somewhat as diagramed conventionally in Figure 10. The

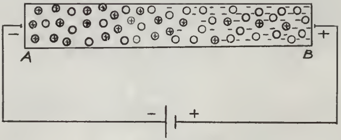

Figure 10

part AB of the circuit shows the metal conductor greatly enlarged. Each open circle represents a neutral atom; each dash a free electron. The circles containing plus signs stand for atoms positively charged, each of which has lost one or more electrons due to the force of the electric field set up between the charged wires near each end (8). The negative wire repels the free electrons in AB and the positive wire attracts them, but the air gaps act as insulators through which electrons cannot pass. Therefore, they accumulate at the positive end of AB in such numbers that their mutual repulsion quickly develops a counter potential sufficient to counteract the force of the external field. Then they come to a standstill. But if the terminal wires from the battery are now touched to AB, as in Figure 11, an outlet for the dammed up electrons is pro-

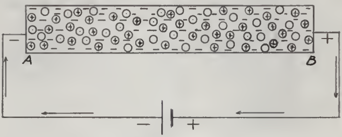

Figure 11

vided and they immediately begin to flow from B toward the positive side of the battery where a deficiency exists. At

the same rate the other wire carries electrons from the negative side of the battery to A, so that the total number within AB remains constant. The drift around the circuit is uniform and continuous for as soon as an electron leaves an atom to move forward in the direction of flow, another is attracted to that atom from behind by the unbalanced positive charge which the atom then possesses.

The time spent by electrons outside of atoms in an ordinary flow of current is believed to be very short compared to the time spent within, and their average velocity through the conductor is only a few centimeters per second (8).

The cause of the flow in the circuit shown is the chemical action of the battery which serves to pump electrons out of the positive side (B) of the circuit and into the negative side (A), creating thereby an unbalanced condition called an electric field. The force of repulsion due to free electrons and ionized (negative) atoms pushes electrons forward in the negative side, while the attraction of unneutralized protons on the positive side exerts a strong pull in the same direction. The two forces combine to form what is known as potential difference, electromotive force, or voltage.

The direction of current flow is, therefore, seen to

be from negative to positive in the external part of a circuit, which is opposite to the classical direction, positive to negative (9). This contradiction is due to a mistaken choice made arbitrarily without experimental proof before the electron was discovered and the process of conduction understood. Several electrical laws and practical rules where direction of flow is involved were formulated during the classical period and are now known to be in error on this point. These will be stated correctly in later paragraphs. For many practical purposes the direction of current is not highly important and may be largely disregarded in certain elementary work, but in the study of electron tubes, chemical reactions, and research in modern physics, where electron behavior is the basis of things, the direction of flow must be understood and duly considered.

Revision of Hand Rules. In the classical period of physics an error was made in arbitrarily assuming that electric current flows in an external circuit from positive to negative, that is, in the direction protons tend to move, whereas current is known at present to be a movement of electrons from negative to positive. Due to this error, certain "right-hand" and "left-hand" rules then formulated should now be oppositely stated.

One of these is the right-hand rule which states that the lines of magnetic force produced by a current around a straight conductor are in the same direction as the fingertips of the right hand, when it grasps the conductor with the thumb pointing in the direction of (positive) current flow. This rule should be changed to read somewhat as follows: The direction of a magnetic field set up by drifting electrons (current) may be indicated by grasping the conductor with the left hand so that the thumb points with the motion of the electrons. The fingertips then indicate the direction of magnetic field.

Similarly, the rule which states that when the coil of an electromagnet is grasped by the right hand so that the fingertips point in the direction of current flow around the coil, the thumb will point toward the north pole of the coil, should be reversed to read "grasped by the left hand", etc.

Fleming devised a three-finger rule (7) to predict the direction of current induced in a closed conductor, as follows: "Let the thumb of the right hand be pointed in the direction of the motion of the conductor across the field, and the forefinger in the direction of the flux, then the middle finger, extended at right angles to the other two, will indicate the direction of the induced current. The

left hand should be substituted for the right in this rule if the current is considered an electron flow.

A similar rule, also credited to Fleming, was used to determine the direction a current-carrying conductor will move when placed in a magnetic field. "Extend the thumb, forefinger, and middle finger of the left hand at right angles to each other. If the forefinger points in the direction of the flux and the middle finger in the direction of the current, then the thumb will indicate the direction of motion of the conductor." Since "current" is really an electron flow in the opposite direction assumed in this rule, the right hand should be used instead of the left.

Convection Current. The flow of electricity through an electrolyte is called a convection current (6). It has been found that when an acid, base, or salt is dissolved in water a portion of the molecules breaks up and exists as separate atoms or groups of atoms, each fragment carrying an electric charge, making it an ion (10). For example, a solution of salt water contains besides neutral molecules of salt, positively charged atoms of sodium and negatively charged atoms of chlorine.

Now, of two electrodes are connected to a battery, as in Figure 12, and placed in a vessel of the solution, the battery establishes a difference of potential between the

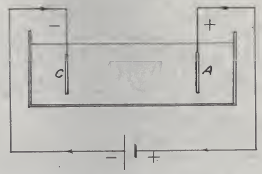

Figure 12

electrodes by removing electrons from the anode A, leaving it positive in charge, and driving them around the circuit onto the cathode C, making it negative. The positive ions of sodium are then repelled by A and driven through the solution toward C which attracts them. Upon reaching C each sodium ion receives an electron from C and becomes a neutral sodium atom. In a like manner, the negative chlorine ions are repelled by C and attracted by A, and upon reaching A give up their electrons which are carried around the circuit again to the cathode C. Only electrons flow in the metallic part of the circuit but two streams of charges, one positive and the other negative, flow in opposite directions to make up the convection current through the solution. It produces heat and a magnetic field, the same as a conduction current.

<u>Resistance. Heating Effect</u>. The magnitude of the current flowing in a circuit depends not only on the poten-

tial difference maintained by the source of electromotive force, but also on the resistance of the circuit as determined by the number and mobility of detachable electrons in the conductor (8). Resistance, or opposition to current flow, is due to several causes. (1) A material having only a few detachable electrons is a poorer conductor than one having many. (2) A small conductor will be poorer than a large one of the same material because of a smaller total number of electrons available for movement. (3) Electrons will drift slower through a long wire than a short one since the fall of potential per unit length, or per atom, is less, which is equivalent to a lower accelerating force. (4) Atoms at higher temperatures are in more violent agitation and are farther apart, due to which electrons have greater difficulty in jumping from one positive atom to another, and in so doing will collide with more neutral atoms, which temporarily stops their motion. All these conditions, producing heat when current flows, combine into one property called resistance, due to which more kinetic energy must be imparted to the moving electrons than would otherwise be necessary. They attain higher velocities, are subject to greater agitation, and to more frequent and violent collisions. The energy thus absorbed by the resistance of a conductor is converted into heat.

Electrolysis. Chemical decomposition by electric current is called electrolysis (6). It was one of the earliest discovered effects of current flow and theories for its explanation were soon attempted (7). Grotthus, about 1805, suggested that each molecule of the electrolyte is made up of two equally and oppositely charged parts which become ions when the molecule breaks up (14). If an electric force is impressed upon the electrolyte, he believed that all the molecules face about with their positive charges pointing toward the negative electrode and the negative charges toward the positive electrode (10). Then they break apart, due to the potential difference, and the positive and negative ions begin to move toward the oppositely charged plates. This process frees ions at each plate and brings the remaining ions together to form new molecules, which rearrange themselves as before in the electric field and then repeat the process. These movements of positive charges in one direction and negative charges in the other together constitute the current (9).

This explanation was found defective, inasmuch as decomposition within the solution requires a certain amount of electric force and no such force could be observed. Helmholtz showed that the interior of an electrolyte cannot withstand the slightest electrostatic stress. So

Clausius later modified the theory by assuming that the molecules are already in active motion, due to their kinetic energy, and by shock of impact break into ions which are attracted toward the plates of opposite sign when introduced.

The discoveries that ions accumulated in greater numbers near the electrodes and that different sorts of ions traveled at different velocities, suggested further modification and gave rise to the "dissociation theory" as developed by Arrhenius, to agree with observed facts concerning certain other physical properties of solutions and with the conception of the atomic structure of electricity indicated by Faraday's laws of electrolysis. Arrhenius offered the suggestion (5), which is the present accepted explanation based on electron theory, that when a salt or other substance is dissolved so as to form an electrolyte, a large per cent of its molecules separate into ions, whether a potential difference is present or not, and are then free, or dissociated, ions. There are always an equal number of positive and negative ions in any such solution and when a potential difference is applied, they begin at once to drift toward the electrodes of opposite sign to which their charges are finally delivered. The negative ion, which is an atom or group of atoms with one or more extra

electrons attached, according to valency, carries these electrons to the positive electrode where it loses them and becomes neutralized, while the positive ion with an equal number of electrons missing moves to the negative electrode and there receives sufficient electrons to neutralize its charge. These neutralized ions then become the products of electrolysis. Within the solution the total current equals the sum of the charges carried in both directions by the two streams of ions.

Electro-Chemical Equivalents. Faraday, about 1837, discovered the laws of electrolysis which bear his name (12). These laws are variously stated (14), but in terms of the electron may be expressed as follows (10):

1. The quantity of any ion liberated from a solution as the product of electrolysis is proportional to the number of electrons (and protons) which have traversed the solution.

2. The quantities of different elements liberated by the passage of the same number of electrons and protons are in the ratio of the atomic weights of those elements divided by the number of electrons added to or removed from each atom in the process of disassociation, that is, atomic weight divided by valence.

The mass of any element transferred and deposited, or

liberated in the case of certain gases, by one coulomb (6.285×10^{18} electrons) is called the electro-chemical equivalent of that element (8) (9). Thus, by many careful measurements, the amount of copper transferred in a solution of copper sulphate is 0.0003294 gram per coulomb, while 0.001118 gram of silver is transferred in a solution of silver nitrate. This last fact forms the basis for the International Ampere, the practical unit of current, which is defined as that steady current which will deposit silver at the rate of 0.001118 gram per second.

The Voltaic Cell. The action of a voltaic cell (7) (9), such as that observed when a plate of zinc and one of copper are immersed in sulphuric acid, was early recognized as being closely related to electrolysis (5) (12). This action was then explained by assuming that a potential difference was established by contact between layers of liquid next to the plates, which ruptured the bond between the positive radical H_2 and the negative radical SO_4. While the hydrogen went to the copper plate, collecting in minute bubbles, the sulphion worked its way to the zinc and united with it to form $ZnSO_4$. The copper thus received a positive charge from the hydrogen and the zinc a negative charge from the sulphion. If the plates were externally joined by a conductor, they became discharged, the positive charges

flowing through the wire from copper to zinc in the form of current (10).

In terms of the electron theory the above action is explained more completely and satisfactorily (6). Many of the acid molecules break up, due to disassociation, when the acid is poured into the water to form the electrolyte, which then consists of water molecules, H_2O; acid molecules, H_2SO_4; positive ions, H; and negative ions SO_4. When the copper plate is placed in the electrolyte it attracts the H ions, itself being negative with respect to the acid. Likewise, the zinc, being positive to the electrolyte, attracts the SO_4 ions, which combine with it to form $ZnSO_4$. In doing so each zinc molecule leaves two electrons behind on the zinc plate, which thus becomes charged negatively. These free electrons flowing through a connecting wire from zinc to copper, neutralize the positive H ions attached to the copper plate and liberate them in the form of hydrogen bubbles. All electric batteries, regardless of the cell constituents, have been found to work on this same general principle, called voltaic action.

The Electromagnetic Units

In addition to a slight electric field caused by stationary charges already discussed, a magnetic field sur-

rounds at right angles any conductor carrying charges in motion. This phenomenon, although the mechanism of its production is as yet not fully determined, is of great importance. It not only provides a method whereby electrical forces may be converted into mechanical forces, as in the motor, and thereby establishes a background for a number of laws and rules of high value, but it also forms the basis of the absolute system of electromagnetic units. The fundamental unit of this system is the abampere (9) (15).

<u>The Abampere</u>. A circular loop of wire, carrying a current of electrons in the direction shown by the arrows in Figure 13, will set up a magnetic field which at the

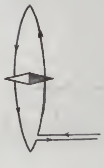

Figure 13

center is perpendicular to the plane of the loop and directed as indicated by the compass. If the radius of the

loop is one centimeter. the current is one abampere when a force of one dyne is exerted on a unit magnetic pole at the center for each centimeter of wire in the loop.

The Abcoulomb. The abampere is a large unit, 3×10^{10} times the size of the electrostatic unit of current, or 6.285×10^{19} electrons per second. This unit current is equivalent to one abcoulomb per second, that is, the unit of quantity of electricity, the abcoulomb, or 6.285×10^{19} electrons, is the quantity carried past any given point in a conductor in one second by a current of one abampere.

The ampere, the practical unit of current, is 1/10 of the abampere. Then the current is one ampere for each coulomb, or 6.285×10^{18} electrons per second flowing in a conductor.

The Abvolt. When a quantity of electrons is transferred in a circuit from a point of lower potential to a point of higher potential, they must pass through some source of electromotive force, such as a battery or generator. Work is done upon them by the source and they acquire potential energy. In other parts of the circuit they may suffer a fall of potential, do work and lose potential energy. If this occurs in a simple resistance circuit, the energy reappears as heat; in a motor it is changed to magnetic or mechanical energy; in an electro-

lytic cell to chemical energy.

One electromagnetic unit of potential difference, the abvolt, exists between two points when the equivalent of one erg of work has been done in carrying one abcoulomb, or 6.285×10^{19} electrons, from one point to the other.

The abvolt is equal to $\frac{1}{3 \times 10^{10}}$ statvolts, which makes it a very small unit, so small that the practical unit, the volt, is 10^8 times as large.

Electric Energy. If the potential difference between two points is E, the work W done on, or by, the quantity Q in moving between the points is $W = QE$ (10). But $Q = It$, where I is the current and t is the time in seconds required for the transfer. Then $W = ItE$, and the energy change per second is $\frac{W}{t} = IE$. That is, the energy lost or gained each second in any part of a circuit is the product of the current strength by the change of potential in that part. This energy will be in ergs per second if the potential difference is measured in abvolts and the current in abamperes. If the current is in amperes and the potential difference is in volts, the energy will be given in joules (10^7 ergs) per second, or watts. This is a power unit and since by Ohm's law $I = E/R$, then power (watts) $= I^2R$.

Comparison of Electrical Units. Although the units

of both the electrostatic and electromagnetic systems are based on the same mechanical principles and concepts, they differ considerably in magnitude because the two systems are based on a different set of electrical characteristics (7). Also, because many of the units are either too large or too small for convenience in measurement and calculation, the practical system was developed for general use (6) (8). A comparison of the numerical relations of the more common electrical units is shown in Table III.

TABLE III

Electrical Units

Magnitude	Practical Units	E. S. Units	E. M. Units
Quantity	Coulomb 6.285×10^{18} electrons	Statcoulomb 3×10^{-9} coulombs	Abcoulomb 10 coulombs
Current	Ampere 6.285×10^{18} electrons/sec.	Statampere 3×10^{-9} amperes	Abampere 10 amperes
Potential	Volt 10^{8} ergs	Statvolt 300 volts	Abvolt 10^{-8} volts
Resistance	Ohm	Statohm 9×10^{11} ohms	Abohm 10^{-9} ohms
Capacity	Farad	Statfarad 9×10^{11} farads	Abfarad 10^{-9} farads

Electromagnetic Induction

Faraday's Discovery. Faraday found (4) (12), about

1831, that if the number of lines of magnetic force passing through a closed circuit is increased or decreased, an electromotive force will be set up in the circuit and an induced current will flow (6)(7)(9)(14)(15).

This curious and surprising effect later proved to be very important, since it involves not only the conversion of energy from the mechanical form to the electrical and back again, typical in the generator and the motor, but also the transfer of energy from one circuit to another, as found in transformers, induction coils, and other devices. But neither Faraday, his contemporaries, nor anyone since that time, has offered a valid explanation of the mechanism by which it is accomplished (10).

One suggestion offered (8), without experimental proof and inadequate in certain cases, is as follows. The energy necessary to make an electron move by this process is stored in its magnetic field when the electron is accelerated and the effect of this energy on nearby electrons is to accelerate them in the opposite direction (5). When electrons are stopped, energy is applied in the opposite sense and the acceleration of nearby electrons is reversed. This is in accord with the law of the conservation of energy and with Newton's third law of motion, but it seems that detailed explanation of phenomena involved must await

further knowledge concerning magnetic fields.

Thermoelectricity

The Seebeck Effect. Seebeck discovered (12) that a current flows through a circuit formed of two different metals when the junction points are at different temperatures (5). This is an example of heat energy being transformed into electrical energy. In the case of a copper-iron couple the current at the hot junction flows from the copper to the iron (classical direction).

The Peltier Effect. The reverse phenomenon, that a cooling or heating occurs at the junctions of dissimilar metals when electric current passes through them, was discovered by Peltier. Thus at a copper-iron junction heat is absorbed when current passes from copper to iron and heat is thrown off when current passes from iron to copper. These thermal effects are proportional to the quantity of electricity flowing. Where the heat is absorbed, heat energy is being transformed into electrical energy and the current is made to flow from a lower to a higher potential. Where heat is liberated, current flows from a higher to a lower potential and the reverse transformation occurs. These effects are due to electromotive forces at the points of junction of the two metals.

<u>The Thompson Effect</u>. Sir William Thompson found that when a single conductor is hot at one point and cold at another, an electromotive force may exist between the points which is opposite in direction in different metals. This results, in a copper-iron couple, in current being driven from the cold end of the copper wire to the hot and absorbing energy, and from the hot end to the cold end of the iron wire, again absorbing energy. Since all the conditions necessary to the Peltier and Thompson effects are present when a thermocouple is in use, it is obvious that the algebraic sum of these two effects is responsible for the total electromotive force of the couple, the Seebeck effect.

<u>Temperature of Inversion</u>. The total thermoelectromotive force is, in general, proportional to the absolute temperature differences of the junctions of the two metals, but is not constant. If this temperature difference is made greater and greater, the potential difference decreases, becomes zero, and finally reverses in sign (6). These relations for a copper-iron couple are shown in Figure 14. When one junction is kept at 0° C. and the temperature of the other is raised, the potential difference increases, but at a decreasing rate, until it reaches 275° C., which is called the neutral temperature (5). Beyond

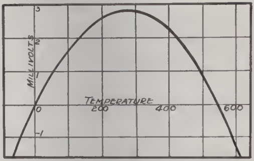

Figure 14

this point the electromotive force decreases and reaches zero value at 550° C., the temperature of inversion. The electromotive force is reversed at still higher temperatures and current flows from the iron to the copper at the hot junction (14).

Thermoelectric Power. The variation of the thermo-electromotive force per degree Centigrade is called the thermoelectric power of the couple. The various metals may be arranged in a thermoelectric series, taking one metal, usually lead, as a reference standard and giving the thermoelectric powers of the other metals with respect to this. Such a table is here given. In order to obtain the thermoelectric power between any two metals of this series, their electromotive force values in microvolts must be subtracted. Under moderate heat the current flows through the heated junction of any pair of these metals from the one appearing first in the series to the one appearing later.

TABLE IV

Thermoelectric Powers in Microvolts per Degree at an Average Temperature of 20° C.

Substance	Microvolts	Substance	Microvolts
Bismuth	-89	Zinc	+3.7
Cobalt	-22	Copper	+3.8
German silver	-12	Iron	-17.5
Lead	0	Antimony	-24.0
Silver	-3	Selenium	-807.0

Electron Explanation. Explanation of thermoelectromotive force in terms of the electron theory is made on the assumption that the electrons per unit volume in one conductor are greater than in the other (5). Then the electronic pressure, which varies with temperature, is greater in the first than in the second so that when the two are brought into contact, a current will flow due to the pressure. It should be kept in mind that this electron drift, or current. is in a direction opposite to the classical direction of current flow, as set forth in preceding paragraphs.

CONCLUSION

Classical theories on electricity and magnetism were based to a great extent on philosophical conjecture, unsupported by experiment. They served in most cases to ac-

count for the facts then known, but were found to fail in many respects as experimental evidence came in and from time to time required change. These theories were many and varied. There was no single basis of broad interpretation.

Today, only the electron theory is acceptable. In higher physics no other is used. Although still incomplete on a few points, it checks with experiment as far as it goes and furnishes the most complete and satisfactory explanation ever formulated.

It would seem advisable, therefore, to use only this theory in elementary physics. It is the writer's conclusion that the authors of textbooks and other literature should abandon the old theories as far as possible as being outgrown and inadequate, and base all experiments, units, rules, and discussions exclusively on modern theory, simply and plainly stated.

It is believed this procedure would simplify the subject matter, create a feeling of confidence in the accuracy and completeness of the treatment, and integrate thinking on the part of both teacher and student.

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LITERATURE CITED

1. Bozorth, R. M.
Present status of ferromagnetic theory. Elect. Engineering. 54:1251-61. Nov. 1935.

2. Crowther, James Arnold
Ions, electrons and ionizing radiations, Sixth Ed. New York. Longmans-Green. 340 p. 1934.

3. DuFay (Mr.)
Letter to the Duke of Richmond on electricity. Phil. Trans. No. 431, 38:258-266. 1734.

4. Faraday, Michael
Experimental researches in electricity. Phil. Trans. 122:125-131. 1832.

5. Fournier, E. E.
The electron theory. New York. Longmans-Green. 327 p. 1916.

6. Gilbert, Norman E.
Electricity and magnetism, Second Ed. New York. 548 p. 1935.

7. Hastings, Charles S. and Beach, Frederick E.
General physics. New York. Ginn. 768 p. 1898.

8. Hector, L. Grant
Introductory physics. New York. American Book Co. 372 p. 1933.

9. Kimball, Arthur L.
A college textbook of physics, Fourth Ed. New York. Holt. 783 p. 1929.

10. Knowlton, A. A.
Physics for college students. New York. McGraw-Hill. 641 p. 1928.

11. Magie, William Francis.
Principles of physics. New York. Century. 570 p. 1911.

12. Magie, William Francis
Source book in physics. New York. McGraw-Hill. 620 p. 1935.

13. Millikan, Robert Andrews
Electrons (plus and minus), protons, photons, neutrons and cosmic rays. Chicago. The University of Chicago press. 492 p. 1935.

14. Reed, John Oren and Guthe, Karl Eugen
College physics. New York. Macmillan. 622 p. 1911.

15. Richtmeyer, Floyd Karker
Introduction to modern physics. New York. McGraw-Hill. 596 p. 1928.

16. Thompson, J. J.
Cathode rays. Phil. Mag. 44, Series 5:293-306. Oct. 1897.

17. Watson, William
Some further inquiries into the nature and properties of electricity. Phil. Trans. No. 485, 45:93-120. 1748.